In the above amendment, claims 16, 17, 26, and 31 have been rewritten in independent form to incorporate the features of the base claim. Applicants respectfully submit that these amendments do not in any way change the scope of these claims, nor were they made for a patentability reason.

DRAWING OBJECTION

In section 2 of the outstanding Office Action, the Examiner has objected to the drawings as failing to show every feature of the invention as specified in the claims. Specifically, the Examiner asserts that the drawings fail to show the curved-shape mesh grids recited in claims 33 and 39. Further, in section 3 of the Office Action, the Examiner has objected to Figure 9 as requiring a legend of --Prior Art--, because only that which is old is illustrated.

Applicants respectfully submit that a Drawing Corrections Authorization Request has been filed on even date herewith, in which Figure 6C has been added to show the curved-shaped mesh grids.

Applicants respectfully submit that the Examiner has mischaracterized the subject matter shown in Figure 9. As clearly indicated in page 10, lines 2-3, the uniform flood beam 52 of Figure 9 is produced by the electron gun (Fig. 2) of the present invention. Contrary to the Examiner's statement, Figure 9 does not show only that which is old. Rather, Figure 9 shows the implementation of the electron gun of

the present invention in a SCALPEL lithography tool, as recited in claim 27.

In view of the drawing correction and above remarks, reconsideration and withdrawal of this objection is respectfully requested.

35 U.S.C. § 112, FIRST PARAGRAPH, REJECTION

Claims 33 and 39 stand rejected under 35 U.S.C. § 112, first paragraph, as not being enabled by the specification. Specifically, the Examiner asserts that the present specification does not enable a person skilled in the art to implement curved-shaped lens arrays, or to configure such curved-shape lens arrays to effect spherical aberration. This rejection is respectfully traversed for the following reasons.

Attached to this Office Action in Appendix A are selected pages from the two following articles:

1) Verster, "On the uses of gauzes in electron optics," Phillips Research Reports, Vol. 18, No. 6, 1963, pp. 495-605; and
2) Van Gorkurn, "Correction of spherical aberration in charged particle lenses using as aspherical foils," Journal of Vac. Sci. Technol. B, Vol. 1, No. 4, 1983, pp. 1312-5.

Applicants respectfully submit that the attached pages of the above-mentioned articles clearly show that the configuration and implementation of curved-shaped mesh grids to correct spherical aberration was within the skill of one of ordinary skill, as early as 1963.

Specifically, see section 1.1 and Fig. 1.1 (page 467) of the Verster article; and section IV and Fig. 1 (pages 1312-3) of the Van Gorkum article.

Therefore, Applicants respectfully submit that one of ordinary skill in the art would have been able to configure the curved shaped mesh grids to reduce spherical aberration in the electron beam, as recited in claims 33 and 39, without undue experimentation. Accordingly, reconsideration and withdrawal of this rejection is respectfully requested.

35 U.S.C. § 102 REJECTIONS

Claims 1-3, 8-10, 15, 16, 19-21, 25-26, 31, and 34 stand rejected under 35 U.S.C. § 102(b) as being anticipated by each of U.S. Patent No. 4,390,789 to Smith et al. (hereafter Smith). Further, claims 1, 2, 8, 11, 13-16, 19, 22, 24-28, and 31 are rejected under 35 U.S.C. § 102(a) as being anticipated by Katsap et al., "Mesh-equipped Wehnelt source for SCALPEL," SPIE, vol. 3777, July 1999, pp. 75-81 (hereafter Katsap). These rejections, insofar as they pertain to the presently pending claims, are respectfully traversed for the following reasons.

Katsap Does Not Qualify as Prior Art

Applicants respectfully submit that the Katsap does not qualify as prior art under 35 U.S.C. § 102(a) against independent claims 1, 16, 25, 26, and 31, as evidenced by the attached Declaration under 37 C.F.R. § 1.132. To qualify as § 102(a) prior art, a publication must be "by another." In the present instance, the authorship of the Katsap article

includes Messrs. Katsap, Waskiewicz, Sewell, and Rouse. Applicants respectfully submit that the subject matter of the Katsap article relied upon by the Examiner to reject independent claims 1, 16, 25, and 31 was conceived by Katsap and Waskiewicz, who are inventors of the present application. Applicants submit that Sewell contributed by providing test facilities, while Rouse provided computational support.

Applicants further respectfully submit that Messrs. Kruit and Moonen, who are also listed as inventors in the present application, did not invent or conceive the claimed subject matter of independent claims 1, 16, 25, 26, and 31. Applicants submit that Kruit and Moonen contributed by pointing out that the concept of the invention could be extended so that the lens array includes 2, 3, or more meshes interacting with each other to achieve desirable effects (e.g., high emittance). Accordingly, Applicants submit that the subject matter of independent claims 1, 16, 25, 26, and 31 was solely conceived by Katsap and Waskiewicz. Therefore, Applicants respectfully submit that the Katsap article cannot be relied upon to reject claims 1, 16, 25, 26, and 31 under § 102(a), because it is not prior art "by another."

Independent Claims 1, 25, 26, and 31; and Claims Depending Thereon

Independent claims 1, 25, 26, and 31 each recite a lens array configured to increase emittance of an electron beam which passes through the lens array. Applicants respectfully submit that Smith fails to teach this feature.

As to Smith, Applicants argued in the Amendment filed April 9, 2001 that Smith fails to disclose a lens array that increases emittance of an electron beam that passes through it. Specifically, Applicants argued that Smith fails to disclose that the lens array causes the electron beam to diverge, thereby increasing emittance.

In sections 23 and 24 of the outstanding Office Action, the Examiner responds by asserting that the lens array inherently increases emittance. The Examiner states that the feature of a divergent electron beam is not recited in the rejected claim, and that Smith's lens array inherently produces a divergent electron beam. Applicants respectfully disagree.

The emittance of an electron beam is a measure of the area occupied by an electron beam, i.e., the size of an electron beam traversing through the lens array. As discussed in page 2, lines 1-2 of the specification, the emittance is defined as the **beam diameter multiplied by the divergence** angle. Therefore, in order for the emittance of an electron beam of a specific diameter to **increase** after passing through a lens array, the beam must **diverge** after passing through the lens array.

In section 26 of the Office Action, the Examiner acknowledges that Smith's system preferably includes a lens array as described in U.S. Patent No. 4,200,794 to Newberry et al. (hereafter Newberry). Newberry specifically discloses a **fin focusing micro l ns array** (see column 4,

lines 25-29 and claim 1). In order to focus a beam, the lens array must cause the beam to converge, as opposed to diverge. Although Newberry's lens array and micro deflector can position the finely focused beam to any area of a target structure (e.g., semiconductor wafer), thereby providing large field coverage (Newberry, column 1, lines 20-30), Newberry teaches away from producing a divergent beam and increasing emittance. Since Smith discloses that it is preferable to implement Newberry's fine focusing micro lens array, it is clear that Smith's lens array **does not** inherently increase beam emittance, but rather, finely focuses the beam to be deflected to a certain position.

Applicants respectfully submit that independent claims 1, 25, 26, and 31 are allowable at least for the reasons set forth above. Applicants respectfully submit that claims 3, 8, 10, 11, and 13 are allowable by virtue of their dependency on claims 1 and 25 at least for the reasons set forth above.

Dependent Claims 15, 19-24 and 34

As amended, claims 15, 19-22, 24, and 34 are now dependent upon claim 17, which is not covered in either of the above rejections. Accordingly, Applicants respectfully submit that claims 15 and 19-24 are not anticipated by Smith by virtue of their dependency on claim 17.

Independent Claim 16

Independent claim 16 recites a method of controlling beam emittance including the step of placing a lens array in an electron gun. Applicants respectfully submit that Smith fails to disclose this feature.

Figure 2 of Smith clearly shows that the lens array 23 is not placed within the electron gun, which comprises elements 13, 14A, 14B, 15A, and 15B. See Smith, column 6, lines 4-7.

Accordingly, Applicants respectfully submit that claim 16 is allowable at least for the above reasons.

For the reasons set forth above, Applicants respectfully request reconsideration and withdrawal of these rejections.

35 U.S.C. § 103(a) REJECTION

Claims 4-7, 11-13, 17-18, 22-24, 29-30, and 35-38 stand rejected under 35 U.S.C. § 103(a) as being unpatentable over Smith in view of U.S. Patent No. 5,376,792 to Schamber et al. (hereafter Schamber). This rejection, insofar as it pertains to the presently pending claims, is respectfully traversed for the following reasons.

In the Amendment of April 9, 2001, Applicants argued that the combination of Smith and Schamber was improper because the only way these references could be combined is by using Applicants' disclosure in hindsight: This is evidenced by the Examiner's failure to provide a showing of the motivation to combine Smith and Schamber as required

by the CAFC in the decision of In re Dembiczak, 50 USPQ2d 1614 (Fed. Cir. 1999).

Specifically, in the previous Office Action of January 8, 2001, the Examiner alleges that one of ordinary skill in the art would have been motivated to add Schamber's liner tube in Smith's system because "liner tube [sic] are commonly used in the art to address vacuum requirement of a charged particle illumination system...Smith acknowledges the necessity of a vacuum...Therefore, one of ordinary skill in the art can easily reason the addition of liner tube [sic] in Smith." (section 13, page 5).

In the Amendment of April 9, 2001, Applicants argued that such a statement would fail to motivate one of ordinary skill to combine Smith and Schamber, because Smith discloses that the housing that surrounds the electron gun and target wafer stage **is already vacuum-sealed** (see column 2, line 66 - column 2, line 2). Therefore, one of ordinary skill in the art would realize that it is not necessary to incorporate Schamber's liner tube in Smith's electron gun.

In the outstanding Office Action, the Examiner fails to respond to Applicants' arguments concerning the motivation to combine. Applicants respectfully request that the Examiner consider their arguments as to the non-combinability of Smith and Schamber, as set forth in the present Amendment, as well as the Amendment of April 9, 2001. Accordingly,

Applicants respectfully request reconsideration and withdrawal of this rejection.

FINALITY OF THE OFFICE ACTION IMPROPER

In section 29 of the outstanding Office Action, the Examiner alleges that Applicants' amendment necessitated the new ground of rejection, and made the Office Action final. Applicants respectfully disagree. In the Amendment of April 9, 2001, no amendment was made to claims 14-16, 19, 22, and 24. Yet, these claims were newly rejected under 35 U.S.C. 102(a) as being anticipated by the Katsap reference. Applicants respectfully submit that, contrary to the Examiner's allegation the new grounds of rejection to claims 14-16, 19, 22, and 24 **were not** necessitated by amendment. Therefore, Applicants respectfully submit that the finality of the present Office Action is improper. Should the Examiner not find the above amendments and remarks to be persuasive, Applicants respectfully request that a new non-final office action be issued.

CONCLUSION

Entry of this Amendment After Final is respectfully requested in that it presents no new issues, the claims being amended to include subject matter already considered by the Examiner.

It is believed that all of the stated grounds of rejection have been properly traversed, accommodated, or rendered moot. Applicant therefore respectfully requests that the Examiner reconsider and withdraw all presently outstanding rejections. It is believed that a full and complete response has been made to the outstanding Office Action, and as such, the present application is in condition for allowance. Thus, prompt and favorable consideration of this amendment is respectfully requested. If the Examiner believes that personal communication will expedite prosecution of this application, the Examiner is invited to telephone the undersigned at (703) 390-3030.

Respectfully submitted,

Dated: 1/2/02

By:
John A. Castellano
Reg. No. 35,904

HARNESS, DICKEY & PIERCE, P.L.C.
P.O. Box 8910
Reston, VA 20195

Attachments: Version with Markings to Show Changes Made
Appendix A

VERSION WITH MARKINGS TO SHOW CHANGES MADE

IN THE SPECIFICATION

the paragraph starting on line 20 of page 3 has been amended as follows:

Figures 6(a), [and] 6(b), and 6(c) illustrate the potential across alternative mesh grids. Figure 6(c) specifically illustrates a mesh grid arrangement where the outward two meshes have a curved shape.

Please amend the paragraph starting on line 10 of page 8 with as follows:

The lens array 80 may be the mesh grid 23 at potential V_1, between liner 20 at potential V_0 as shown in Figure 6, or include two grids 23 and 23' at the potentials illustrated in Figure 6(a) or three grids 23, 23', 23" at the potentials illustrated in Figures 6(b) and 6(c), or any other configuration which contains a grid mesh with an electrostatic field perpendicular to the gridplane.

IN THE CLAIMS

Claim 14 has been canceled.

Claims 15-17, 19-21, 24, 26, 31, and 34 have been amended as follows:

15. (Amended) The method of claim [14] <u>17</u>, wherein the lens array is placed in a drift space of the charged particle illumination system component.

16. (Amended) [The] <u>A</u> method of [claim 14] <u>controlling beam emittance, comprising:</u>

<u>placing a lens array in a charged particle illumination system component</u>,

wherein the illumination system component is an electron gun.

17. (Amended) [The] <u>A</u> method of [claim 14] <u>controlling beam emittance, comprising:</u>

<u>placing a lens array in a charged particle illumination system component</u>,

wherein the illumination system component is a liner tube, connectable to an electron gun.

19. (Amended) The method of claim [14] <u>17</u>, wherein the lens array including at least one mesh grid.

20. (Amended) The method of claim [14] <u>17</u>, wherein the lens array including at least two mesh grids.

21. (Amended) The method of claim [14] 17, wherein the lens array including at least three mesh grids.

24 (Amended) The method of claim [14] 17, wherein the lens array has a transparency between 40-90%.

26. (Amended) [The] An electron beam exposure tool of [claim 25] comprising:

a charged particle illumination system component including a lens array placed in said charged particle illumination system component,

wherein said lens array is configured to increase emittance of an electron beam passing through said lens array,

wherein said lens array is placed in a drift space of said charged particle illumination system component.

31. (Amended) [The apparatus of claim 1] A charged particle illumination system component, comprising:

a lens array configured to be placed in said charged particle illumination system component,

wherein said lens array is configured to increase emittance of an electron beam which passes through said lens array,

wherein said lens array increases emittance of an electron beam by producing a divergent beam from an incoming electron beam.

34. (Amended) The method of claim [14] 17, further comprising the step of:

directing an electron beam through said lens array to increase emittance of said electron beam.

APPENDIX A

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ON THE USE OF GAUZES IN ELECTRON OPTICS *)

by J. L. VERSTER

Abstract and introduction

It was discovered in the late twenties that electrons, emerging from an object, could be made to give an image, after having traversed a properly shaped electromagnetic field. Hence it was discovered that such a field acts upon electrons as a lens acts upon rays of light. It was realized very soon that imaging by means of electrons and the focussing of electron beams opened up new possibilities in many branches of science and technology, to mention the electron microscope and the cathode-ray oscilloscope. Therefore a new branch of applied physics, electron optics, came into being. Electron optics studies the trajectories of electrons in electromagnetic fields in order to describe the optical properties of such fields.

Electron optics can be treated in the same way as light optics, at least theoretically, once the electron-optical index of refraction is introduced. This follows from the facts that rays of light satisfy Fermat's principle, in which the index of refraction appears, and that the trajectories of electrons satisfy Maupertuis' principle of least action, both principles being variational equations with the same conditions. If the electron-optical index of refraction is defined, an important chapter of light optics, such as the theory of geometrical optics, can be applied to electron optics.

It might appear that electron optics is only a special kind of light optics and therefore cannot lead a life of its own. That this is not true will become clear if electron optics is considered closer.

An electron-optical lens consists of an electromagnetic field, whose electrostatic part is brought about by electrodes and whose magnetic part is brought about by pole pieces, by coils or by both.

If it is required that the region where the electrons move is free from electrodes and pole pieces, then the field in this region can only be controlled by electrodes, etc., at the boundary. Therefore the most obvious difference with light-optical lenses is that, in order to know either the field or the electron optical index of refraction, a boundary value problem must be solved.

Since the electrons move in a field, their trajectories will in general be curved. In order to obtain the trajectories, certain differential equations, whose coefficients depend on the field, must be integrated.

Consequently, with regard to the calculation of the rays, electron optics is completely different from light optics.

*) Thesis, Technological University, Delft, October 1963.
Promotors: Professors B. le Poole and L. J. F. Broer.

CHAPTER 1

ELECTRON OPTICAL PROPERTIES OF TWO-ELECTRODE LENSES WITHOUT AND WITH A FOIL

1.1. Introduction

The question of to which extent the properties of electron optical lenses can be improved by the use of a foil, has been answered only incidentally. Symmetrical three-electrode electrostatic lenses, whose middle electrode consists of a gauze, have received much attention from French authors. Such a lens has been designed by Cartan as early as 1937 and will therefore be called a Cartan lens. Grivet [1]), in his text-book, has dealt with the Gaussian properties of Cartan lenses and with the scattering of the electrons by the gauze. These problems have been attacked originally by Bernard and by Bertein. Bernard [2]) has derived a first order approximation of the focal distance of Cartan lenses. Further he has derived an expression for the spherical aberration, taking the discontinuity of the field strength into account, and has observed that the spherical aberration might become negative if the potential of the foil is lower than the potential of the outer electrodes [3]). Bertein [4]) has dealt with the scattering of the electrons by the gauze-shaped electrode. Gianola [5]) has proposed to correct the spherical aberration by means of a uniform electrostatic field between two foils.

In order to compare the properties of one-foil lenses with those of lenses without a foil, we shall deal with three kinds of two-electrode lenses. The

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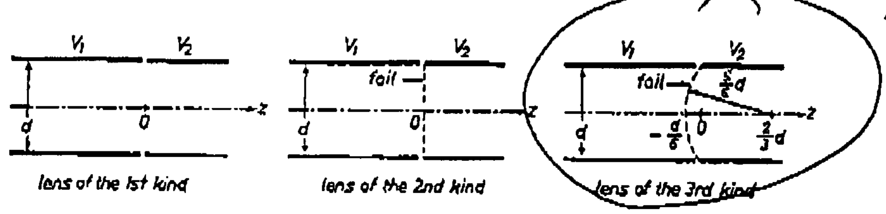

Fig. 1.1. The three kinds of lenses, whose properties will be dealt with. The gap between the electrodes is at $z = 0$. The foil intersects the axis at $z = z_2$. The foil of the lens of the second kind is flat and therefore $z_{2(2)} = 0$. The foil of the lens of the third kind is part of a sphere with radius $(5/6)\,d$ and centre at $z = (2/3)\,d$, therefore $z_{2(3)} = -(1/6)\,d$.

electrodes of the lens of the first kind consist of two tubes of equal diameter, in the second and the third kind of lens, one of the tubes is replaced by a flat and a spherical foil respectively. Especially the second kind of lens is basic, since two such lenses placed back to back yield a Cartan lens if the potentials of the outer electrodes are equal, and yield a lens of the first kind if the potential of the foil is midway between the potentials of the outer electrodes.

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(2.14)

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(2.16)

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(2.17)

If $(d_c - q_c) \gg s$, $(d_a - q_a) \gg s$ and V_c, V_g and V_a are kept constant, $\bar{\phi}(z)$ will remain the same after the grid is replaced by its mirror image with respect to the plane $z = \frac{1}{2}(q_a - q_c)$. If the potential distribution is the one shown by Fig. 2.3a one has $D_a(d_c, d_a) = -V_g/V_a$ before the replacement, and $D_c(d_a, d_c) = -V_g/V_a$ afterwards. Hence one finds from comparing (2.17) with (2.10) that $f_a(\infty) = f_c(\infty)$, which proves (2.16).

In order to compare the penetration factors of grids of different shapes we introduce the reduced penetration factor D' by means of

$$D' = (d_a - q_a)D_a/s = (d_c - q_c)D_c/s, \tag{2.18}$$

if $d_a - q_a \gg s$ and $d_c - q_c \gg s$.

It is easily seen from considerations of scaling that D' only depends on the shape of the grid and not on its size. From (2.17) and (2.18) we obtain

$$V_g = V_{cg} + D's(\bar{E}_a - \bar{E}_c). \tag{2.19}$$

2.3. Results of the measurement of D_a and D'

The penetration factor is measured for four kinds of gauzes, which we shall now describe. First a gauze of intersecting wires of circular cross section, which has a pitch s in both directions and a wire diameter $2r$ (see Fig. 2.4a). Second a gauze from a sheet of thickness 0·0107s, which has square holes of

Layouts

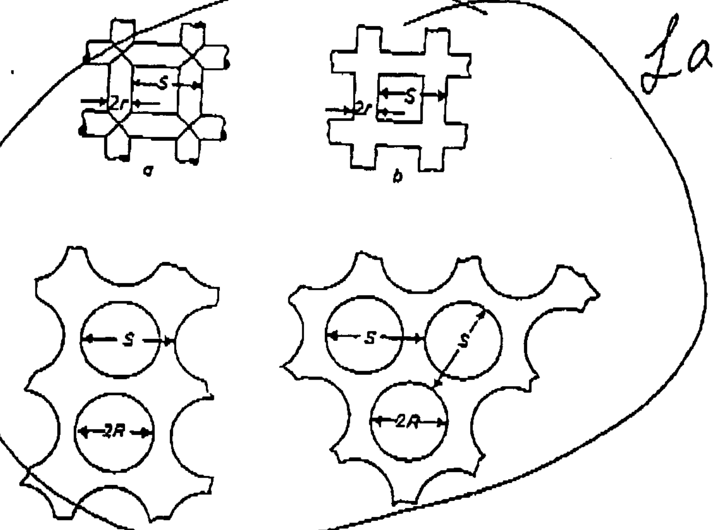
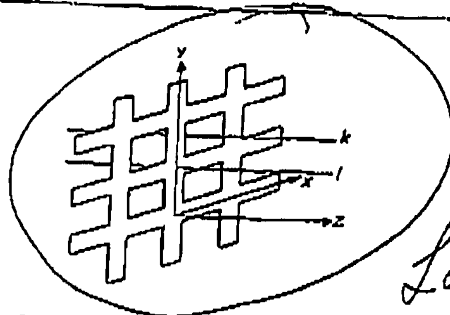


Fig. 2.4. Four types of gauzes of which the penetration factor is measured. The gauze shown in a) consists of round intersected wires. The gauzes shown in b), c) and d) are made from a thin plate into which holes are cut.



Layout

Fig. 2.2. A gauze made of a flat plate with square holes. The co-ordinate system used and the lines k and l are shown.

The potential shows a ripple in any plane parallel to the grid. In order to get an idea of how rapidly the ripple decreases if the distance from the plane to the grid increases the potential distribution between the grid and cathode will be represented by a function that contains enough parameters to satisfy the boundary condition at the cathode and at a gauze of arbitrary shape. This requirement can be met by the sum of a linear function of z and the product of two Fourier series, that are periodic in x and y respectively, each containing a term that is independent of x and y and of which the coefficients depend on z. This function can be worked out into

$$\phi(x,y,z) = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} a_{mn} f_{mn}(x,y,z), \qquad (2.1)$$

where $f_{mn}(x,y,z) = \cos(2\pi mx/s_x + \kappa_m) \cos(2\pi ny/s_y + \lambda_n)\, h_{mn}(z)$, s_x and s_y denoting the pitch of the gauze in the x and the y direction respectively. In order that ϕ satisfies Laplace's equation, h_{mn} is chosen so that f_{mn} satisfies Laplace's equations, i.e.:

$$\Delta f_{mn} = [-4\pi^2\{(m/s_x)^2 + (n/s_y)^2\}\, h_{mn} + h_{mn}'']\, f_{mn}/h_{mn} = 0.$$

This differential equation is solved by $h_{00}(z) = az + b$ and

$$h_{mn}(z) = A \exp\{2\pi\sqrt{(m/s_x)^2+(n/s_y)^2}\, z\} + B \exp\{-2\pi\sqrt{(m/s_x)^2+(n/s_y)^2}\, z\}$$

if m and n are not both zero.

We now assume that s_x and $s_y \ll d_c$.

Since the amplitude of the ripple remains finite when z goes to $-\infty$, B must be zero. Hence, between grid and cathode

$$f_{mn}(x,y,z) = \cos(2\pi mx/s_x + \kappa_m) \cos(2\pi n/s_y + \lambda_n) \exp\{2\pi\sqrt{(m/s_x)^2+(n/s_y)^2}\, z\}. \qquad (2.2)$$

In the case of a gauze for which $s_x = s_y = s$, the Fourier component of the ripple that has the same period ($m = 1$, $n = 0$ and $m = 0$, $n = 1$) as the

Correction of spherical aberration in charged particle lenses using aspherical foils

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(Received 3 June 1983; accepted 22 August 1983)

The struggle to overcome spherical aberration in electron lenses has a long history. One of the weapons against this lens defect has been the use of foils, as suggested by Scherzer. Most attention was paid to the use of an electrostatic foil lens having a weak negative power and an accompanying negative spherical aberration. It was used to correct the positive spherical aberration of a magnetic lens. Some work has been devoted to the use of foils in purely electrostatic lenses, trying to create a positive lens free from spherical aberration. Flat foils and even spherical ones were used. It turned out that only weak positive lenses without spherical aberration could be created using these foils. It is shown here that a strong positive lens free from spherical aberration can be created using an aspherical foil. More specifically, the radius of curvature of the foil should increase with increasing distance from the rotation axis of the lens. The properties of these lenses are analyzed using ray tracing through numerically calculated fields. All higher order aberrations are thus taken into account. Using this type of analysis, it is proved that positive aspherical foil lenses show very little or even negative spherical aberration, depending on the geometry of the foil and/or its position in the two tube equidiameter accelerating lens.

PACS numbers: 41.80.Dd

I. INTRODUCTION

Rotational symmetric lenses for charged particles are always positive, provided that they are free of space charge and have object and image in field-free space. Scherzer has shown[1] that the spherical aberration of these lenses is always positive too. This lens defect restricts the resolution in electron microscopes, contributes to the spot size in cathode ray tubes, etc. It has been the subject of many research activities for over 50 years.[2]

One of the ways to overcome the spherical aberration in rotational symmetric lenses is the use of foils, as was shown by Scherzer in 1947.[3] Since then many people have followed up this suggestion. The main interest came from groups working on magnetic lenses, trying to correct the positive spherical aberration by means of a weak negative foil lens with accompanying negative spherical aberration.[4–15]

This paper will focus on purely electrostatic foil lenses. Liebmann[16] found in 1949 that an electrostatic lens with a wire mesh had a spherical aberration far less than that of lenses without a mesh. Verster[17] published data of foil lenses of the types shown in Fig. 1, obtained using an electrolytic tank based ray tracer. These are the simplest types of foil lenses: two equidiameter tubes at different potential, one of them covered with a foil. Verster found a slight reduction of the spherical aberration going from the foilless lens to the flat foil lens. The spherical foil showed about an equal performance.

Thomson[18] studied negative electrostatic foil lenses, exploiting their negative spherical aberration for the correction of electrostatic lenses. Munro and Wittels[19] published formulas for the aberration coefficients in lenses containing foils. Finally, Van der Merwe[20,21] published work on foil lenses starting from elementary potential distributing functions.

In this paper it will be shown that a strong reduction, cancelling, and even reversing the sign of the spherical aberration of pure electrostatic lenses is possible using an *aspherical* foil. This has some analogy to light optical lenses where the only possibility to eliminate the spherical aberration of a single lens is by using aspherical surfaces.

In Sec. II the definition of and reason for spherical aberration in electrostatic lenses will be given. Section III contains a discussion of the properties of a flat foil lens, mainly with regard to their spherical aberration properties. The accelerating two tube lens with a spherical foil is treated in Sec. IV. In Sec. V the new type of lens with an aspherical foil is introduced. The conclusions follow in Sec. VI.

II. SPHERICAL ABERRATION

Lenses do have a greater power for rays passing through the outer zones of the lens compared to paraxial rays. This effect is called spherical aberration.

The general reason for the spherical aberration of rotational symmetric lenses free of space charge is that the radial

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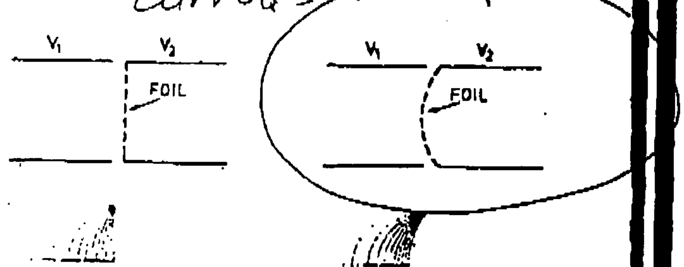

FIG. 1. Foil lenses with flat and spherical foil as analyzed by Verster (Ref. 17) and the equipotential lines in these lenses at voltages of 0.1 (0.1) 0.9 of the voltage difference.

force on the charged particles is not linear in the radial distance from the axis, as it should be for a weak ideal lens. The higher order terms (r^3, r^5, etc.) are the cause of the aberration.

III. FLAT FOIL LENSES

A two cylinder equidiameter lens without a foil consists of a positive and negative lens part. The overall lens action is always positive. If a flat conducting foil is placed on the end of one f the two cylinders (Fig. 1), a purely positive or negative lens results. The sign of the lens power depends on the voltage ratio V_2/V_1. It will be a strong lens, since the power does not result anymore from a partial compensation of a positive lens by that of a negative one.

As mentioned in the previous section, a weak lens without spherical aberration must have the property that the radial field strength integrated along the trajectory is proportional to the radial distance from the axis. In a weak lens this distance is constant for a particle entering the lens parallel to the axis. It can be shown,[21] based on Gauss' law, that this is equivalent to the requirement that the field strength is constant at the flat foil. This also entails a constant induced surface charge density.

When in a weak foil lens the absolute value of the surface charge density increases with the radius r, the spherical aberration will have the same sign as the lens power. A decrease will result in the opposite sign.

For lenses that are not weak or have a curved foil, the above remarks may serve as a guideline only. For a strong lens one might want a weakly varying surface charge.

In a flat foil lens of the given type the field strength increases with increasing radial distance r, as can be seen in the equipotential line plot in Fig. 1. The field strength is inversely proportional to the distance between the foil and the adjacent equipotential line. Thus, this lens will have a positive spherical aberration when the lens is positive, and a negative spherical aberration when the lens is negative.

IV. SPHERICAL FOIL LENSES

A possible improvement of foil lenses lies in the deformation of the foil. A logical step is making the foil spherical with radius of curvature ρ. Verster[17] did use $R/\rho = 0.6$ (Fig. 1), with R the lens radius.

Lenses with different values of ρ were analyzed. For $R/\rho > 1$, the second cylinder was given a radius equal to ρ.

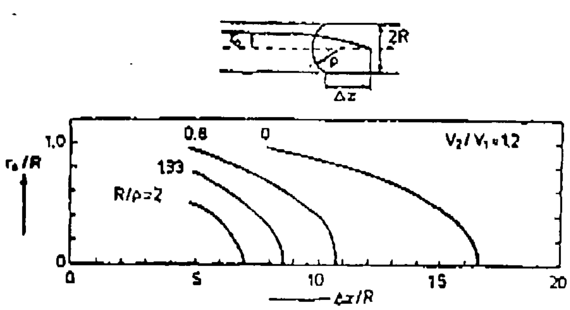

FIG. 2. Distance of axial crossing from gap (Δz) as a function of initial radial distance from axis r_0 for parallel incoming rays in spherical foil lens with V_2

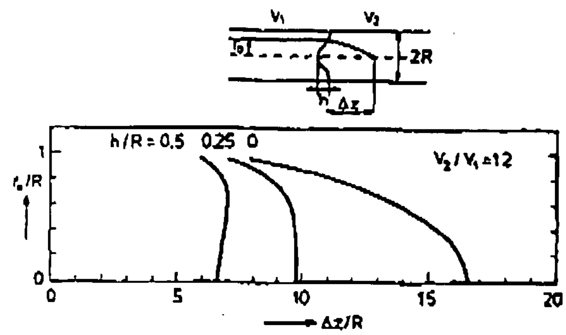

FIG. 3. Distance of axial crossing from gap (Δz) as a function of initial radial distance from axis r_0 for parallel incoming rays in Bessel foil lenses with $V_2/V_1 = 1.2$ and different heights of foil.

The spherical aberration behavior of these spherical foil lenses was evaluated by numerically tracing rays through the calculated fields. The voltage ratio was chosen 1.2 to stay in the weak lens regime. Rays were started parallel to the axis and the axial crossing position Δz relative to the gap of the lens was determined. It is plotted in Fig. 2 on the horizontal axis. Vertically the initial radius r_0 is given. For the flat foil lens ($R/\rho = 0$) the spherical aberration is strongly positive since the outer rays cross the axis at a shorter distance than inner rays. Note that rays with r_0 values up to nearly full lens filling are given. For smaller radii of curvature, the lens becomes stronger (Δz becomes smaller), but all lenses exhibit a positive spherical aberration, as was found by Verster for $R/\rho = 0.6$.[17] Making the foil spherical has no dramatic effect on the spherical aberration behavior.

V. ASPHERICAL FOIL LENSES

To circumvent the problems encountered using spherical foils, it was decided to use aspherical forms with a radius of curvature increasing with increasing distance from the axis. As a basic form the central part (until the first minimum) of a zero's order Bessel function J_0 (see Ref. 22) was chosen. In

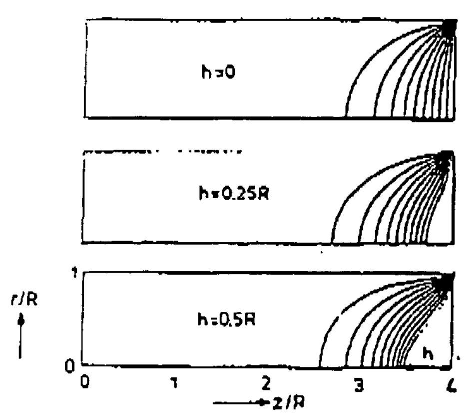

FIG. 4. Equipotential lines in lenses with Bessel-type foil at voltages of 0.1 (0.1) 0.9 times the voltage difference and heights of the foil $h/R = 0, 0.25, 0.5$ with R the lens radius.

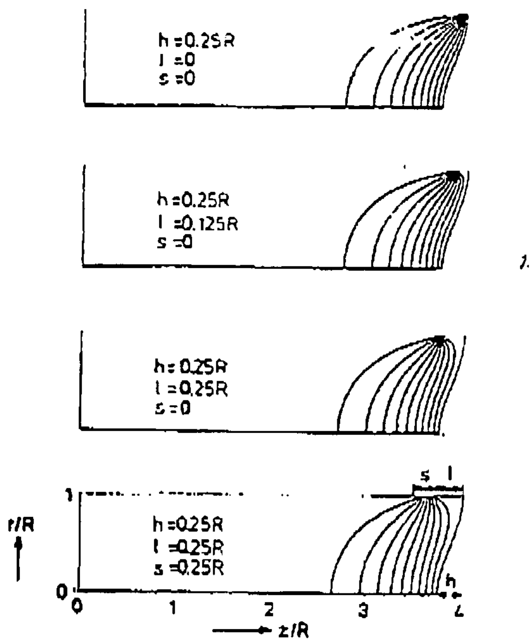

FIG. 5. Equipotential lines in lenses with Bessel-type foil at voltages 0.1 (0.1) 0.9 times the voltage difference; heights $h/R = 0.25$, varying rim length l, and gap lengths s.

this region it is very similar to a cosine function. A free parameter is still the height h of the dome of the foil relative to its base (Fig. 3). The first minimum is positioned at R.

The spherical aberration behavior was evaluated the same way as for the spherical foil lenses (Sec. IV). The results for $h/R = 0, 0.25$, and 0.5 and a voltage ratio V_2/V_1 of 1.2 are shown in Fig. 3. It is seen that the power of the lenses increases with h. Moreover, the third order aberration (for rays closest to the axis) is zero for h/R around 0.25 and is negative for $h/R = 0.5$. Higher order aberrations cause the increase in the spherical aberration again for greater values of r_0. Note again that the maximum r_0 value is $0.95R$: nearly the full aperture of the lens is used. It is clear that a third order

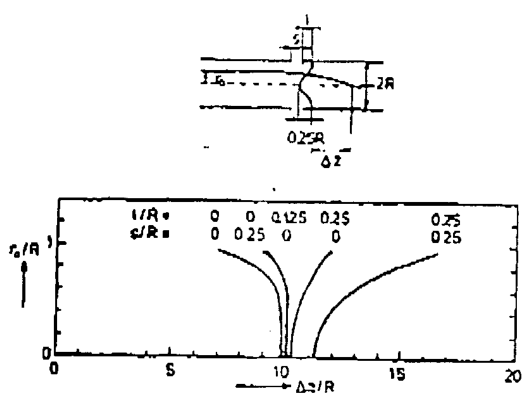

FIG. 6. Distance of axial crossing Δz from rim of foil as a function of initial radial distance from axis r_0 for parallel incoming rays in Bessel foil lenses with $V_2/V_1 = 1.2$ and height of foil $h/R = 0.25$, varying height of rim l, and gap length s.

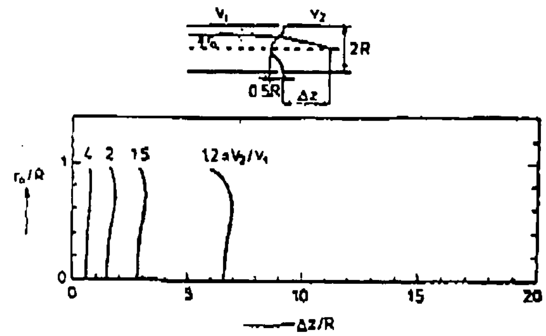

FIG. 7. Distance of axial crossing Δz from gap in lens as a function of initial radial distance from axis r_0 for parallel incoming rays in Bessel foil lenses with height of foil $h/R = 0.5$ and varying voltage ratio V_2/V_1.

coefficient is insufficient to describe the spherical aberration behavior over the full lens aperture.

Figure 4 shows the equipotential lines in the three mentioned lenses. The distance between the foil and the adjacent equipotential line is inversely proportional to the field strength at the foil. From these illustrations it is clear that for $h/R = 0.25$ the field strength at the foil is nearly constant over a large part of the aperture, corresponding to a small spherical aberration. For $h/R = 0.5$, the field even decreases in the central part of the foil, corresponding to a negative spherical aberration. The correspondence in behavior with Fig. 3 is clear.

The equipotential lines at the outside all converge due to the assumed negligible narrow gap. This suggests that the performance can be improved by adding a rim and/or gap of lengths l and s. The behavior in terms of spherical aberration can again be predicted from the resulting equipotential lines plotted in Fig. 5 for different values of s and l and $h/R = 0.25$. For $l/R = 1/8$ and $s/R = 0$ a nearly full compensation of the spherical aberration is expected. For the last lens with $l/R = s/R = 0.25$ a negative spherical aberration is expected. This is confirmed by the ray tracing results in Fig. 6. It shows that by proper choice of l and/or s it is possible to eliminate (at least within the accuracy of the plot) the spherical aberration over the full aperture of the lens.

It is also clear from Fig. 6 that a positive lens with a relatively strong negative spherical aberration can be created by choosing gap and/or rim length.

Figure 7 shows what happens when the voltage ratio is increased for the lens with $h/R = 0.5$. It has a negative spherical aberration for $r_0/R < 0.5$, the inner half of the rays. For a large voltage ratio V_2/V_1 the spherical aberration stays slightly negative over the whole aperture! This is a very strong lens with an image side focal distance of $0.85\ D$. It shows that the possibility exists to create a lens with the desired strength and spherical aberration behavior by proper choice of the height h of the foil, the rim length l, and the gap length s.

VI. CONCLUSIONS

The possibility exists to eliminate the spherical aberration in a two cylinder equidiameter lens over its full aperture by using an aspherical foil. Leaving the axis, the radius of curva-

ture of the foil should initially increase. The correction works even for strong lenses. The design criterium of a constant field strength at the foil, a requirement for weak lenses only, is a good starting point in the design of all lenses free from spherical aberration.

By proper choice of parameters such as height of the foil, length of the gap and/or rim, it is possible to adjust the spherical aberration to the requirements of the designer. One might want a positive lens without spherical aberration, or one that has a negative spherical aberration to cancel positive spherical aberration in other parts of the electron optical system.

Note added in proof: Meisburger and Jacobson [Optik 62, 359 (1982)] published data recently on a lens with two aspherical surfaces.

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